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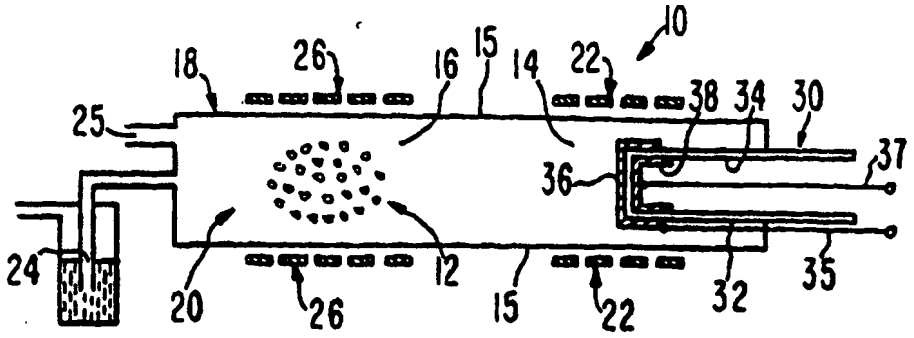

(57) Abstract

A high temperature fuel (10) having first and second temperature zones (14, 16) for directly converting carbon fuel (12) to electrical energy comprises a first heat source (22), a second heat source (26), and a housing (18) that includes a non-porous section (15) and a solid electrolyte (30) having first and second electrolyte surfaces (32, 34) to which first and second electrodes (36, 38) are electrically connected. The first heat source (26) establishes first temperature zone (14) in the vicinity of the solid electrolyte (30) for adjusting the conductivity of the solid electrolyte (30) and electrodes (36, 38). The second heat source (26) is positioned in the vicinity of non-porous section (15) of housing (18) a distance from first heat source (22) to establish second temperature zone (16). A fuel compartment (20) defined by the first electrolyte surface (32) of solid electrolyte (30) and the non-porous section (15) of housing (18) spans first and second temperature zones (14, 16) to allow intermixing of oxygen provided through solid electrolyte (30) and a carbon fuel (12) which is located primarily in second temperature zone (16). The fuel compartment (20) may be provided with a gas inlet (25), gas outlet (27), and return line (31) through which non-reactive gas can be circulated to enhance the mixing of oxygen with carbon fuel (12). To generate electrical power, second temperature zone (16) is adjusted to a temperature which favors the complete oxidation of carbon fuel (12), first temperature zone (14) is adjusted to a temperature that minimizes the resistance of solid electrolyte (30) and electrodes (36, 38), and oxygen is provided by supplying an oxygen containing gas to the second electrolyte surface (32) of solid electrolyte (30).

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DIRECT ELECTROCHEMICAL CONVERSION OF CARBON TO ELECTRICAL ENERGY IN A HIGH TEMPERATURE FUEL CELL

Technical Field

This invention relates to the field of fuel cells, and in particular to the field of high temperature fuel cells for the direct electrochemical conversion of carbon to electrical energy.

Background of the Invention

High temperature fuel cells employing solid electrolytes to convert the chemical energy stored in gaseous fuels to electrical energy have been reported. In the most common examples of these fuel cells, oxygen is the working medium for electrochemical conversion, moving as oxide ions across the solid electrolyte to react with gaseous fuels such as coal derived gases, H_2 , and CH_4. Electrons consumed in the reduction of oxygen to oxide ions at the cathode side of the electrolyte are released from the oxide ions at the anode side of the electrolyte to generate current flow in an external circuit. These fuel cells operate most efficiently when the gaseous fuels are completely oxidized at the anode to CO_2 and H_2O in the case of carbon containing fuels or H_2O in the case of H_2. The efficiency of solid oxide fuel cells is also improved by operating them at high temperatures where ohmic losses due to the impedances of the solid electrolyte and the electrode are minimized.

The conversion of the chemical energy to electricity provided by the combustion of gaseous fuels is inherently less efficient than the direct conversion of pure carbon from coal. For example, in the case of H_2 and CH_4, stable H-H and C-H bonds must be broken before the energy releasing reactions can occur. Consequently, less chemical energy is available to generate electricity than in the case where carbon is oxidized directly.

Attempts have been made to use coal as a carbon source in solid oxide fuel cells. However, in these cases a separate gasification step is employed to convert the coal into a gaseous fuel prior to the combustion process. Typically, this is done by passing wet

oxygen (O_2 plus H_2O) over coal at elevated temperatures to generate CO and H_2, and the CO is subsequently reacted with O_2 to produce CO_2. The combustion of coal using this intermediate conversion process is still less efficient than the direct combustion of coal. For example, the gasification process used to generate CO for electrochemical conversion is a thermal process, and therefore subject to the energy conversion limits of the Carnot cycle. In addition, the primary reaction at the anode of the fuel cell is the oxidation of CO to CO_2, which yields approximately half as much chemical energy for conversion to electricity as the oxidation of C to CO_2.

Despite the advantages of direct electrochemical conversion of coal to electricity, there are a number of obstacles to producing a practical fuel cell for such purposes. Chief among these obstacles are the competing temperature requirements of the solid electrolyte and the combustion reactions of the fuel cell. For example, carbon can react directly with O_2 to generate either CO or CO_2, with complete oxidation being favored at lower temperatures (below about 700° C). On the other hand, the impedances of the solid electrolyte and its electrodes for ionic conduction increase with decreasing temperature. For this reason, solid electrolyte fuel cells are typically run at temperatures above approximately 900° C. As a result, a conventional solid oxide fuel cell could not efficiently convert coal directly to electricity since either the thermodynamic efficiency of the combustion reactions or the conductivity of the electrolyte and electrodes could not be independently optimized.

In sum, it is desirable to develop methods for the direct conversion of solid fuels such as coal into electrical energy, to eliminate the energy and efficiency costs of intermediate gasification steps. However, in order to operate efficiently, a solid fuel cell must address the problems presented by the competing temperature requirements of the electrolyte and fuel cell reactions, as well as the reaction kinetics problems of solid fuel reactants.

Disclosure of Invention

The present invention is a high temperature fuel cell (10) that uses an oxide ion conducting solid electrolyte (30) in conjunction with separate temperate zones (14, 16) to optimize the direct electrochemical conversion of carbon fuels (12) to electrical energy. The high temperature fuel cell (10) of the present invention eliminates the need for an intermediate step in which the carbon fuel (12) is converted into a gaseous fuel prior to combustion. Combustion efficiency is optimized by providing fuel cell (10) with separate temperature zones (14, 16) for the carbon fuel (12) and the solid electrolyte (30), respectively, allowing simultaneous and independent control of the reactions which drive the electrochemical process and the ionic conductivity of the solid electrolyte (30).

In accordance with the present invention, a high temperature fuel cell (10) comprises a first heat source (22), a second heat source (26), and housing (18), which includes a non-porous section (15) and a solid electrolyte (30). The solid electrolyte (30) has first and second electrolyte surfaces (32, 34) on which are deposited first (anode) and second (cathode) electrodes (36, 38), respectively, for conducting currents generated by high temperature fuel cell (10). The first heat source (22) is located in the vicinity of solid electrolyte (30) of housing (18) to establish a first temperature zone (14) of fuel cell (10). The second heat source (26) is positioned in the vicinity of the non-porous section (15) of housing (18) at a location that is removed from first heat source (22), to establish a second temperature zone (16) in fuel cell (10). A fuel compartment (20) which communicates between the first and second temperatures zones (14, 16) is formed in housing (18) by the non-porous section (15) and the first electrolyte surface (32) of solid electrolyte (30). The fuel compartment (20) includes a gas inlet (25) and may include a liquid seal (24) for adjusting the pressure in the fuel compartment (20).

Electrical power is generated from the high temperature fuel cell (10) by placing carbon fuel (12) in the second temperature zone (16) of the fuel compartment (20) and heating the carbon fuel (12) to a temperature that favors complete oxidation of the carbon fuel (12) to CO_2. First temperature zone (14) is adjusted by means of first heat source (22) to a temperature at which ohmic losses due to the impedances of the solid electrolyte

(30) and electrodes (36, 38) are minimized. Oxygen is then provided to the carbon fuel (12) by supplying an oxygen containing gas to the second electrode (38) of the solid electrolyte (30), the driving force for conduction of oxide ions through the solid electrolyte (30) being provided by the difference between the activities of oxygen in the fuel compartment (20) and in the oxygen containing gas supplied to the second electrode (38).

A high temperature fuel cell (60) may be implemented for commercial purposes using a fluidized bed reactor (50) for the fuel compartment (20). In a fluidized bed reactor (50), fine particles of carbon fuel (12) are suspended by blowing a non-reactive gas in through the bottom (52) of the reactor (50). Second heat sources (26) are located along the outer surface of the reactor (50) to maintain the carbon fuel (12) at the desired temperature. A collection of solid electrolytes (30), each having an electrode pair (36, 38) as described above, is arrayed along the reactor (50) in a temperature zone controlled by first heat sources (22). Oxygen containing gases supplied to the second electrodes (38) of these solid electrolytes (30) provide oxygen to the suspended carbon particles (12) in a manner analogous to that described for a single fuel cell (10).

Brief Description of the Drawings

Fig. 1A is a diagram of a cross-section of one embodiment of a high temperature fuel cell (10) in accordance with the present invention.

Fig. 1B is a diagram of a cross section of another embodiment of a high temperature fuel cell (10) in accordance with the present invention.

Fig. 2 is a diagram of the theoretical activities of oxygen as a function of temperature for the partial and complete oxidation of a carbon fuel (12).

Fig. 3 is a diagram of the expected and measured (squares) open circuit voltages generated between the electrodes (36, 38) of the high temperature fuel cell (10) of Fig. 1A as a function of the temperature of the carbon fuel (12).

Fig. 4 is a diagram of a high temperature fuel cell (60) in accordance with the present invention where the non-porous section (15) of housing (18) is a fluidized bed reactor (50).

Fig. 5 is a diagram of a high temperature fuel cell (70) in accordance with the present invention comprising a collection of high temperature fuel cells (10) positioned in a container vessel (74).

Detailed Description of the Preferred Embodiments

Referring to Fig. 1A, there is shown a high temperature fuel cell **10** for efficiently converting the chemical energy of carbon directly into electrical energy by electrochemical means fuel cell **10** comprises a first heat source **22**, a second heat source **26**, and a housing **18** which includes a non-porous section **15** and a solid electrolyte **30**. Solid electrolyte **30** has a first electrolyte surface **32** which is in electrical contact with a first electrode **36**, and a second electrolyte surface **34** which is in electrical contact with a second electrode **38**. Electrical connections **35, 37** are in electrical contact with first and second electrodes **36, 38**, respectively, for conducting electrical current generated by fuel cell **10**.

First heat source **22** is positioned in the vicinity solid electrolyte **30** to establish a first temperature zone **14** in the vicinity of solid electrolyte **30**. Second heat source **24** is located in the vicinity of non-porous section **15** at some distance removed from first heat source **22** to establish a second temperature zone **16**. First and second heaters **22, 26** may be for example resistive heating elements or radiative heaters arrayed circumferentially around housing **18**. First and second temperature zone **14, 16** are not sharply defined, but rather gradually merge one into the other. Non-porous section **15** of housing **18** and first electrolyte surface **32** of solid electrolyte **30** together define a fuel compartment **20**, which spans first and second temperature zones **14, 16** so that oxygen from solid electrolyte **30** and carbon fuel **12** may pass freely between first and second temperature zones **14, 16**. In general, the geometry of fuel cell **10** and the relative sizes of first and second temperature zones **14, 16** are selected so that the temperature of carbon fuel **12** is determined primarily by the temperature of second temperature zone **16**. In one embodiment of fuel cell **10** a gas inlet **25** and a liquid seal **24** may be provided for purging fuel compartment **20** and maintaining the pressure in fuel compartment **20** at a constant level during combustion.

In the embodiment shown in Fig. 1A, solid electrolyte **30** has a cylindrical shape and extends into non-porous section **15** so that first electrode **36** at closed end **40** is within first temperature zone **14** and proximate to second temperature zone **16**. An oxygen containing gas such as air or pure oxygen is supplied to second electrode **38** of solid electrolyte **30**, where it is oxidized and transported across solid electrolyte **30** to first electrode **26** as oxide ions. At first electrolyte **36**, oxygen is regenerated by reduction of the oxide ions, and made available for combustion by carbon fuel **12** in fuel compartment **20**. The geometry of solid electrolyte **30** in Fig 1A enhances the intermixing of oxygen provided through solid electrolyte **30** with carbon fuel **12**.

Referring now to Fig. 1B, there is shown an alternative embodiment of high temperature fuel cell **10**, wherein solid electrolyte **30** and housing **18** together form an elongated fuel cell **10**. Oxygen is provided to carbon fuel **12** by supplying an oxygen containing gas to solid electrolyte **30**, where its oxidation and reduction at second and first electrodes **38, 36**, respectively, generates electrical current which is collected by connections **35, 37**. A Non-reactive gas such as for example CO_2, N_2, Ar, or He entering fuel cell **10** at first end **17** of housing **18** may be used to entrain carbon fuel **12** in second temperature zone **16** and transport it toward solid electrolyte **30** for reaction with oxygen. Non-reactive gas and any unreacted carbon fuel **12** or oxygen will exit temperature fuel cell **10** at second end **19** of housing **18**.

Alternatively, a return line **31** may be provided to allow for recirculation of reactants through temperature fuel cell **10**. In the embodiment of Fig. 1B, a non-reactive gas enters fuel compartment **20** through gas inlet **25**, and exits through gas outlet **27**, where it is recirculated by return line **31** back to gas inlet **25**. This arrangement allows oxygen from solid oxide **30** in first temperature zone **14** to be entrained in the stream of non-reactive gas and passed through return line **31** to second temperature zone **16** for reaction with carbon fuel **12**. It also minimizes the amount of carbon fuel **12** that is left unconsumed by fuel cell **10**. Other fuel cells **10**, in which the geometries of non-porous section **15** and solid electrolyte **30** are selected to enhance the mixing of oxygen and carbon fuel **12**, may be contemplated within the scope of the present invention.

Non-porous section **15** provides structural support for solid electrode **30** and together with solid electrolyte **30** forms fuel compartment **20**. Non-porous section **15** may be selected from among refractory materials that are oxidation and reduction resistant and that do not display the mixed electronic and ionic conducting properties discussed below. For example, non-porous section **15** may be a ceramic material or an oxidation resistant metal or alloy.

Ideally, solid electrolytes **30** for use in fuel cells **10** in accordance with the present invention are ionic conductors and electronic insulators, since the greater conductivity of electrons would otherwise effectively eliminate any charge conduction by oxide ions. Suitable solid electrolytes **30** may be generated for example by doping the oxides of Bi, Zr, Hf, Th, and Ce with either alkaline earth oxides such as CaO or MgO, or rare-earth oxides such as Sc_2O_3, Y_2O_3, or Yb_2O_3. Solid electrolytes are discussed below in conjunction with the temperature dependence of their conductivities.

Second electrode **38**, the cathode of fuel cell **10**, provides a pathway for the electrons necessary to reduce oxygen to oxide ions for transport across solid electrolyte **30**. First electrode **36**, the anode of fuel cell **10**, provides a pathway to conduct away electrons released by the oxidation of oxide ions. Oxygen is provided to second electrolyte surface **34** of solid electrolyte **30** by directing either an oxygen-containing gas or pure oxygen at electrode **38**, where the oxygen is reduced to oxide ions. Electrode **38** must thus allow the mass transport of oxygen in the form of oxide ions between the oxygen-containing gas and second electrolyte surface **34** of solid electrolyte **30**. Similarly, electrode **36** must allow oxide ions to pass from first electrolyte surface **32** of solid electrolyte **30** into electrode **36** to be oxidized. Since metals are not generally good ionic conductors, electrodes **36, 38** are typically made by applying a porous metallic paste to first and second electrolyte surfaces **32, 34** of solid electrolyte **30**. In a preferred embodiment of the invention, the porous metallic paste is made from an oxidation resistant metal such as a noble metal. For example, when a porous platinum paste is used to make electrode **38**, the reduction of molecular oxygen to oxide ions occurs at three phase line boundaries where solid electrolyte **30**, electrode **38**, and the oxygen-containing gas all come into direct contact.

This three phase coincidence of materials is necessary since the poor ionic conductivity of metal electrode **38** requires that reduction of oxygen occurs where solid electrolyte **30** is available to conduct away the resulting oxide ions. The use of porous platinum for electrodes **36, 38** maximizes the number of three phase line boundaries available for mass transport of oxygen.

In a more preferred embodiment of the invention, electrode **38** is made from a mixed conducting oxide material, since such materials are capable of conducting both oxide ions and electronic species (electrons or holes). In this way, first and second electrolyte surfaces **32, 34** can be completely coated with mixed conducting oxide electrodes **36, 38**, respectively. The mixed conducting properties of the oxide allows electrodes **36, 38** to conduct not only the electrons necessary for the reduction/oxidation reactions but also to conduct the oxide ions to and from the underlying solid electrolyte **30**. Suitable mixed conducting oxide materials may be selected from a variety of oxides, including those having perovskite, pyrochlore, sheelite, and rutile structures. For example, mixed conducting perovskites may be selected from compositions having the formulas:

$$La_{1-x}\,Sr_x\,MnO_3 \qquad \text{(Eq. I)},$$

where x is between zero and one, or:

$$La_{1-x}\,Sr_xCo_yFe_{1-y}O_3 \qquad \text{(Eq. II)},$$

where x is between zero and one, and y is also between zero and one.

In order to operate fuel cell **10** efficiently, two principal means of energy loss must be effectively controlled. These are the incomplete oxidation of carbon fuel **12** and the ohmic losses created by transporting oxide ions across solid electrolyte **30** and electrodes **36, 38** having finite impedances. In the first case, less oxygen is consumed and less energy is generated for conversion to electricity when carbon fuel **12** is incompletely oxidized. In the second case, additional energy generated by electrochemical conversion of carbon fuels **12** is consumed in moving charges through solid electrolyte **30**. Temperature zones **14, 16** created by heat sources **22, 26** provide means to optimize operation of fuel cell **10** in view of these inefficiencies.

In the simplest case of a pure carbon fuel **12**, combustion occurs by two different reactions. These reactions are the partial oxidation of carbon to CO:

$$C + \tfrac{1}{2} O_2 \rightarrow CO \qquad \text{(Eq. III)},$$

and the complete oxidation of carbon to CO_2:

$$C + O_2 \rightarrow CO_2 \qquad \text{(Eq. IV)}.$$

If carbon fuel **12** contains hydrogen and for example sulfur impurities, water and oxides of sulfur are also produced during oxidation. More generally, carbon fuels **12** such as coal may contain volatile impurities such as hydrogen and hydrocarbon compounds in addition to sulfur and ash. While many of these impurities can be removed by coking or desulfurization pretreatments, fuel cells **10** in accordance with the present invention may use untreated coal as carbon fuel **12**, the combustible impurities being oxidized along with carbon fuel **12**.

The reaction of Eq IV is preferred since it consumes more oxygen and makes available more chemical energy for conversion to electrical current. However, both reactions will occur during combustion of carbon fuel **12**, and the degree to which the reaction of Eq. IV predominates over the reaction of Eq. III depends in part on the temperature at which the reactions occur.

Referring to Fig. 2, there is shown a graph of the theoretical activity of O_2 as a function of the reaction temperature for the reactions of Eq. III and IV. The lower the activity (partial pressure) of O_2, the greater the tendency of reaction to proceed to completion (product formation). It is clear from the curves of Fig. 2 that the reaction of Eq. IV is favored at temperatures below about 1000^o K (approximately 700^o C) and that the predominance of the reaction of Eq. IV over the reaction of Eq. III increases as the temperature of the reactants is decreased. Thus, combustion of carbon fuel **12** to completion will be more favored thermodynamically the more the reactant temperatures are reduced below about 700^o C. However, the temperature of fuel compartment **20** must still be kept high enough so that the reaction of Equation IV proceeds at a reasonable rate. Thus, in the preferred embodiment of the present invention, the reactants are maintained at about 700^o C by using heat source **22** to adjust the temperature of fuel compartment **20**.

Another factor affecting the rates of reaction of Eqs. III and IV is the amount of carbon available to react with the O_2. Where carbon is the limiting reactant in the combustion of carbon fuel **12** as may be the case where a solid carbon fuel **12** is used, O_2 will be in excess. Consequently, the activity of the O_2 increases, decreasing the chemical driving force that generates electric current. This effect can be countered by making a solid carbon fuel **12** available to O_2 in a more reactive form. For example, it is known that graphite is more reactive at its edges than it is at the flat surfaces of the graphite sheets. Thus, where carbon fuel **12** is in the form of a solid carbon such as coal or graphite, it is preferably provided in the form of a finely divided powder.

The second factor that may reduce the efficiency of fuel cell **10** is the ohmic loss attributable to the conduction of oxide ions through solid electrolyte **30** and electrodes **36, 38**. Solid electrolytes **30** having sufficient ionic conductivities for use in fuel cells **10** may be obtained for example by doping oxides of Bi, Zr, Hf, Th, and Ce with either alkaline earth oxides such as CaO or MgO, or a rare-earth oxide such as Sc_2O_3, Y_2O_3, or Yb_2O_3. The actual ionic conductivities of solid electrolyte **30** will depend on the temperature at which solid electrolyte **30** is maintained. For example, the ionic conductivity of ZrO_2 stabilized by Sc_2O_3 increases from approximately 0.01 Ω^{-1} cm^{-1} at 650° C to approximately 0.1 Ω^{-1} cm^{-1} at 900° C. Consequently, fuel cells **10** operated at about 650° C will have ohmic losses due to I^2R heating that are approximately an order of magnitude greater than fuel cells **10** operated at 900° C, making it more efficient to operate at higher temperatures. Where solid electrolyte **30** is Y_2O_3 stabilized ZrO_2, fuel cell **10** is typically operated at temperatures above about 800° C. This is accomplished in fuel cells **10** of the present invention by using first heat source **22** to adjust first temperature zone **14** around solid electrolyte **30**.

Referring now to Fig. 3, there is shown a diagram of the theoretical and measured (squares) open circuit voltages for fuel cell **10** of Fig. 1A, generated with solid electrolyte **30** as a function of temperature. It is clear from the curves of Fig. 3 that the complete oxidation of carbon is a more efficient means of producing electrical energy than the partial oxidation, since the complete oxidation reaction generates comparable open circuit

voltages while consuming twice as much oxygen as the partial oxidation reaction. Since the power output of fuel cell **10** is the product of the voltage and current generated, optimizing the temperature of temperature zone **16** for complete oxidation of carbon fuel **12** enhances the efficiency of fuel cell **10**.

Fuel cells **10** may be modified to generate electricity on a commercial scale by using a fluidized bed reactor **50** as non-porous section **15** of housing **18**. Referring now to Fig. 4, there is shown a fuel cell **60** comprising a fluidized bed reactor **50** having a collection of solid electrolytes **30** mounted in a wall **56**. Each of solid electrolytes **30** has first and second electrolyte surfaces **32, 34** which are in electrical contact with first and second electrodes **36, 38**, respectively. Electrodes **36, 38** from each solid electrolyte **30** may be connected in series or in parallel, according to the use to which fuel cell **60** is applied.

Fluidized bed reactor **50** includes a bottom surface **52** having gas inlets **25**. In operation, fine particles of carbon fuel **12** are introduced into fuel compartment **20** of fluidized bed reactor **50**. A stream of non-reactive gas is blown in through gas inlets **25** to distribute fine particles of carbon fuel **12** throughout fuel compartment **20**. A gas outlet **27** allows the pressure of non-reactive gas in fuel compartment **20** to be controlled. As in fuel cell **10**, fuel cell **60** includes first heat source **22** for adjusting temperature zone **14** in the vicinity of solid electrolytes **30** and second heat source **26** for adjusting the temperatures of carbon fuel **12**.

Referring now to Fig. 5, there is shown a fuel cell **70** comprising a collection of fuel cells **10** as shown in Fig 1B. As shown, fuel cell **70** has a gas line **72** for recirculating a non-reactive gas through fuel cells **10**, to maximize mixing of carbon fuel **12** and oxygen form solid electrolytes **30** and minimize loss of uncombusted carbon fuel **12**. A gas inlet **76** allows an oxygen containing gas to be introduced into a container vessel **74**, where it is provided to solid electrolytes **30**. First and second heat sources **22, 26** establish first and second temperature zone **14, 16** for solid electrolytes **30** and carbon fuel **12**. Electrical leads **35, 37** from first and second electrolyte surfaces **36, 38**, respectively, of solid

electrolytes **30** are connected to sum the current generated by individual fuel cells **10** and provide more power.

The above description is included to illustrate the operation of the preferred embodiments and is not meant to limit the scope of the invention. The scope of the invention is to be limited only by the following claims. From the above discussion, many variations will be apparent to one skilled in the art that would yet be encompassed by the spirit and scope of the invention.

What is claimed is:

Claims

1. A high temperature fuel cell having two temperature zones for directly converting a carbon fuel to electrical energy, the fuel cell comprising:

a housing including a non-porous section and a solid electrolyte, the solid electrolyte having first and second electrolyte surfaces to which first and second electrodes, respectively, are attached, the second electrolyte surface and the non-porous, electrically conducting section forming a fuel compartment;

a first heat source positioned on the housing proximate to the solid electrolyte for establishing a first temperatures zone in the fuel compartment in the vicinity of the solid electrolyte; and

a second heat source positioned on the housing at a distance removed from the first heat source for establishing a second temperature zone in the fuel compartment; whereby

electrical current is electrochemically generated by the mass transport of oxygen across the solid electrolyte for the combustion of the carbon fuel in the fuel compartment when an oxygen containing gas is brought into contact with the outer surface of the solid electrolyte.

2. The high temperature fuel cell of claim 1, wherein the solid electrolyte is an oxide ion conducting solid electrolyte.

3. The high temperature fuel cell of claim 2, wherein the oxide ion conducting solid electrolyte is selected from the group comprising the oxides of Hf, Zr, Bi, Ce, and Th doped with oxides from the group comprising alkaline earth metals and rare earth metals.

4. The high temperature fuel cell of claim 3, wherein the oxide ion solid electrolyte is zirconium oxide doped with yttrium oxide.

5. The high temperature fuel cell of claim 1, wherein the first and second electrodes are each formed from a porous, oxidation resistant metal.

6. The high temperature fuel cell of claim 5, wherein each porous, oxidation resistant metals is a noble metal.

7. The high temperature fuel cell of claim 1, wherein the first and second electrodes are each formed from a mixed conducting oxide.

8. The high temperature fuel cell of claim 7, wherein the mixed conducting oxide is selected from the group of materials having rutile, perovskite, pyrochlore, and sheelite structures.

9. The high temperature fuel cell of claim 8, wherein the mixed conducting oxide has a perovskite structure and a composition having the formula $La_{1-x}\ Sr_x\ MnO_3$, where x is between zero and one.

10. The high temperature fuel cell of claim 8, wherein the mixed conducting oxide has a perovskite structure and a composition having the formula $La_{1-x}\ Sr_xCo_yFe_{1-y}O_3$, where x is between zero and approximately one and y is between zero and approximately one.

11. The high temperature fuel cell of claim 1, wherein the temperature of the solid electrolyte is adjusted to between approximately 700^o C and approximately 1100^o C.

12. The high temperature fuel cell of claim 11, wherein the temperature of the carbon fuel is adjusted to between approximately 500^o C and approximately 1000^o C.

13. The high temperature fuel cell of claim 12, wherein the temperature of the carbon fuel is adjusted to between approximately 500^o C and approximately 800^o C.

14. A high temperature fuel cell according to claim 1, wherein a gas inlet line and a liquid seal are attached to the fuel compartment, for adjusting the pressure in the fuel compartment.

15. A high temperature fuel cell according to claim 1, wherein a gas inlet and an gas outlet coupled together by a return line are each attached to the fuel compartment, for circulating a non-reactive gas through the fuel compartment to enhance the combustion of the carbon fuel.

16. A method for directly converting carbon fuels to electrical energy using a high temperature fuel cell having a housing that includes a fuel compartment defined by a non-porous section and a solid electrolyte having first and second electrolyte surfaces to which first and second electrodes are electrically connected, the fuel cell also having separately adjustable first and second temperature zones for independently controlling the temperature of the solid electrolyte and a carbon fuel within the fuel compartment, the method comprising the steps of:

adjusting the first temperature zone to a temperature that minimizes the impedances of the solid electrolyte and electrodes;

adjusting the second temperature zone to a temperature at which complete oxidation of the carbon fuel to CO_2 is favored over its oxidation to CO;

supplying an oxygen containing gas to the second electrolyte surface of the solid electrolyte; and

drawing electrical current from the first and second electrodes.

17. The method of claim 16, wherein the oxygen containing gas is a gas having a high oxygen activity.

18. The method of claim 17, wherein the oxygen containing gas having a high oxygen activity is selected from the group comprising oxygen and air.

19. The method of claim 18, wherein the first temperature zone is adjusted to a temperature of between approximately 700° C and 1100° C.

20. The method of claim 18, wherein the second temperature zone is adjusted to a temperature of between approximately 500° C and approximately 1000° C.

21. The method of claim 18, wherein the solid electrolyte is an oxide ion conducting solid electrolyte selected from the group comprising the oxides of Bi, Zr, Bi, Ce, and Th doped with oxides from the group comprising the alkaline earth oxides and rare earth oxides.

22. The method of claim 21, wherein the oxide ion conducting solid electrolyte is yttrium-stabilized zirconium oxide.

23. The method of claim 18, wherein the carbon fuel comprises fine particles of carbon fuel for providing greater surface area and enhanced rates of oxidation.

24. The method of claim 18, wherein the carbon fuel is coal.

25. The method of claim 24, wherein the coal is untreated.

26. The method of claim 18, wherein the first and second electrodes are mixed conducting oxides.

27. The method of claim 25, wherein the mixed conducting oxides are selected from the group of materials having rutile, perovskite, pyrochlore, and sheelite structures.

FIG.1A

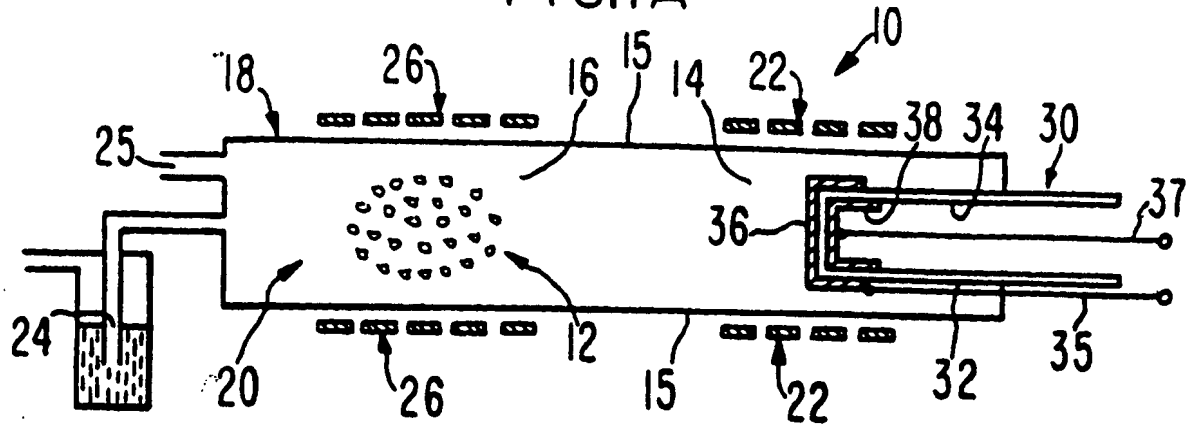
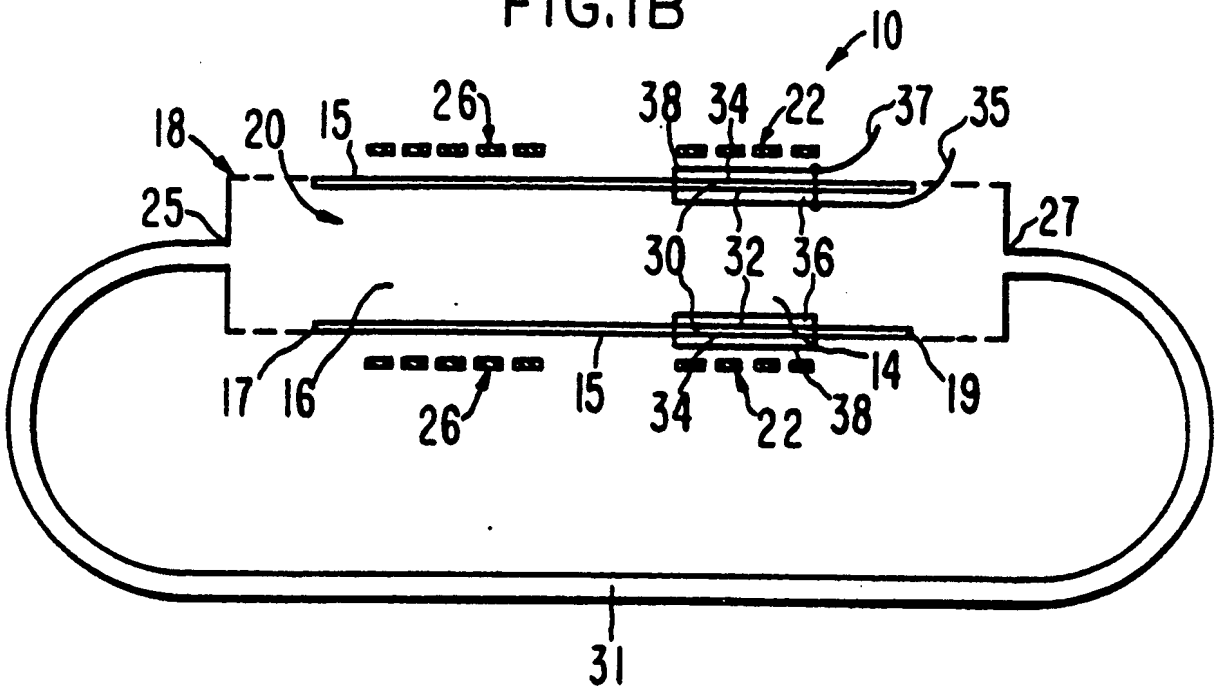

10
18
26
16
15
14
22
38
34
30
25
37
36
24
20
12
26
15
22
32
35

FIG.1B


10
18
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26
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32
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19
31

FIG.2

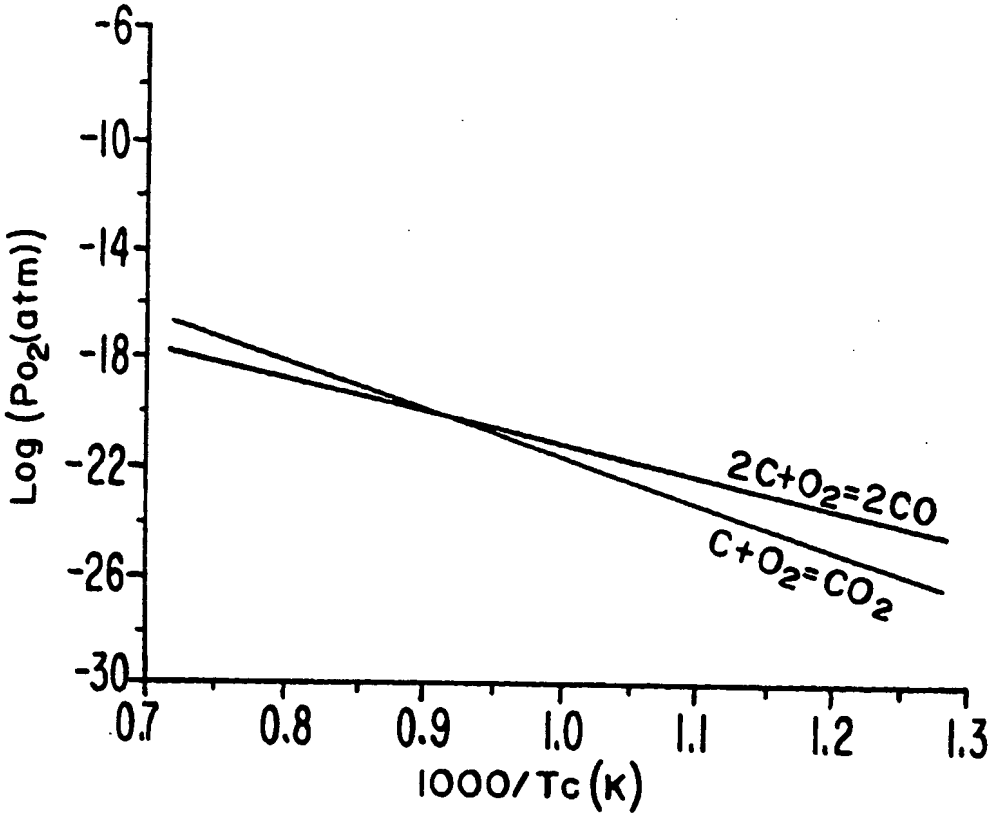
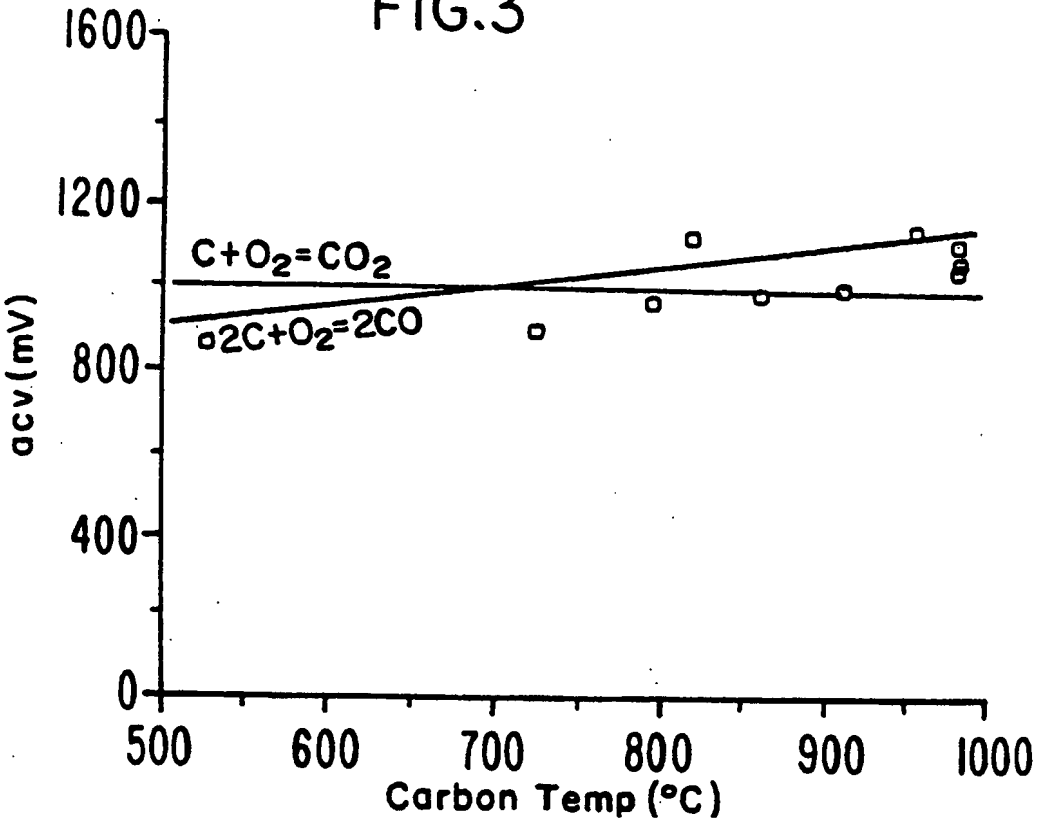

-6
-10
-14
-18
-22
-26
-30
Log (Po_2(atm))
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1000/Tc (K)
$2C+O_2=2CO$
$C+O_2=CO_2$

FIG.3


1600
1200
800
400
0
acv (mV)
500
600
700
800
900
1000
Carbon Temp (°C)
$C+O_2=CO_2$
$2C+O_2=2CO$

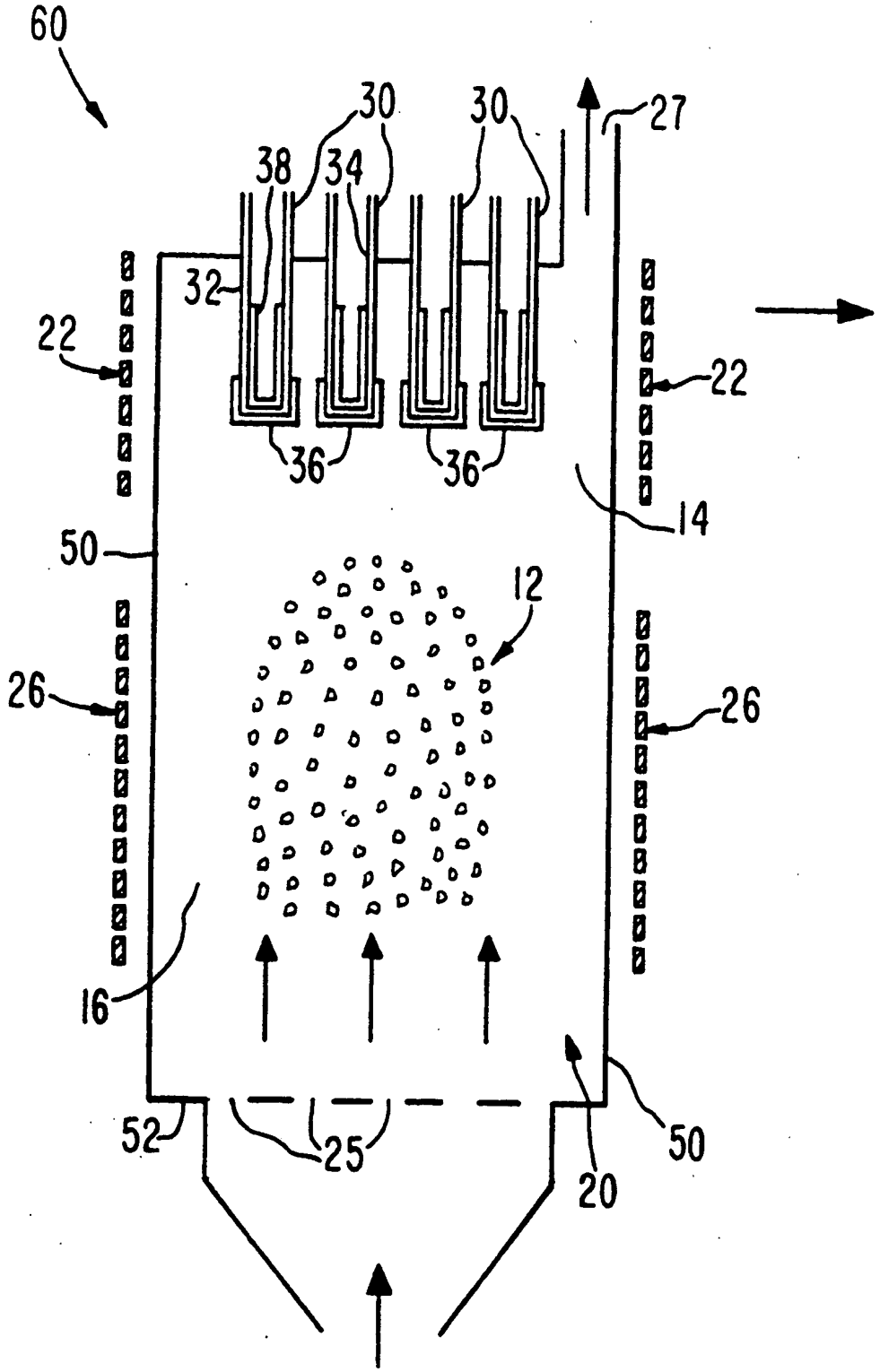


FIG. 4

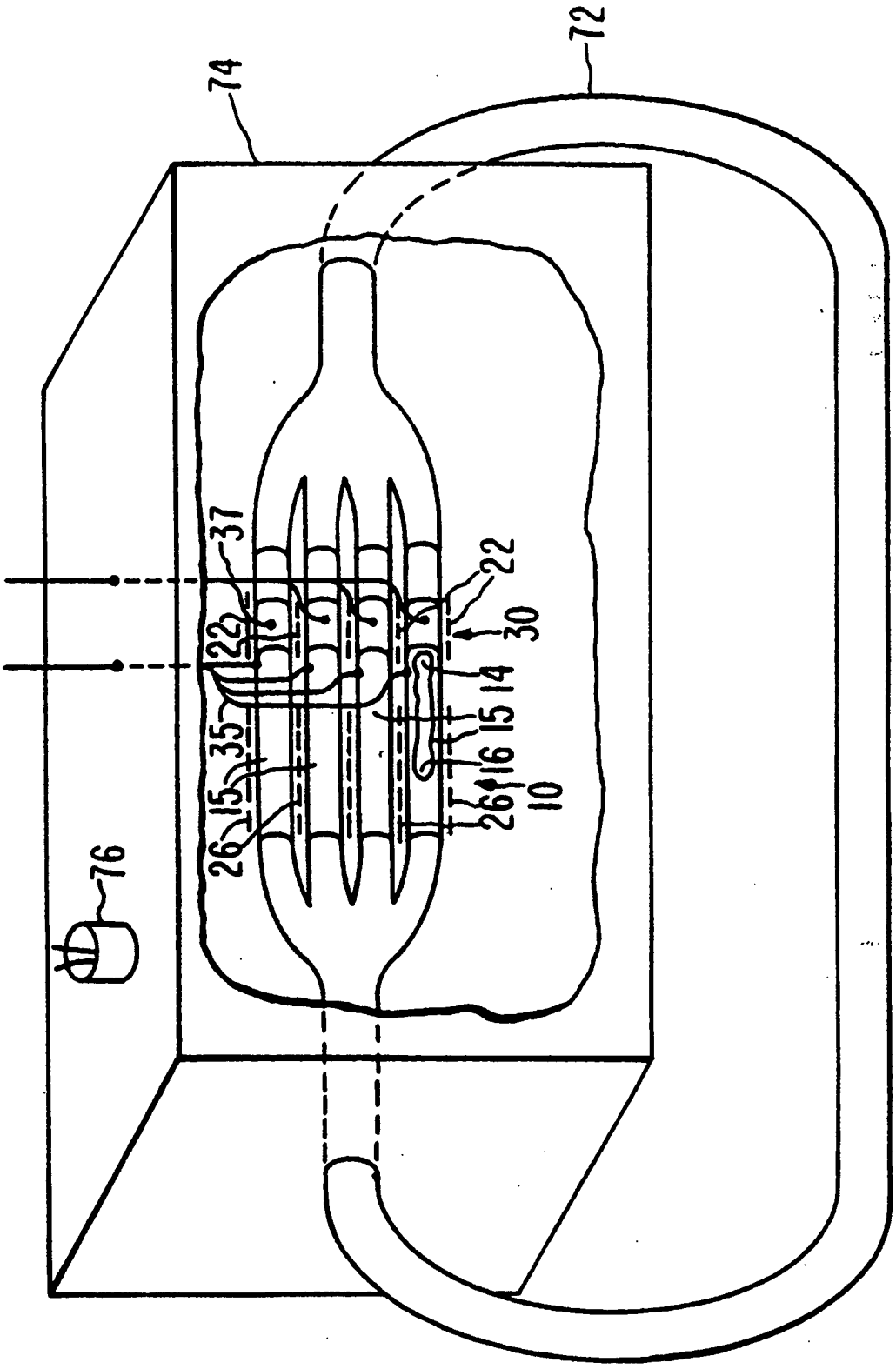


FIG.5